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Fatigue Assessment and Extreme Response Prediction of Ship Structures

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ABSTRACT

In this thesis, a simplified narrow-band approximation model is proposed to estimate fatigue damage of ship structures, and an efficient method for extreme response predictions is also developed using upcrossing spectrums of ship responses.

The proposed fatigue model includes two main parameters, significant stress range h_s and zero upcrossing frequency f_z. The first parameter is assumed to be proportional to significant wave height H_s through a factor C, derived from a linear hydrodynamic theory. The value of C depends on the mission conditions. The zero upcrossing frequency is approximated by the encountered wave frequency, where the wave period T_z is deduced to be an explicit function of H_s. The fatigue model is validated by the "accurate" rainflow method with less than 10% of discrepancy. The uncertainties of fatigue life predictions are studied by the safety index, employing the proposed fatigue model. It is shown that the safety index computed using the fatigue model agrees well with that computed from the measurements.

With respect to the fact that ship responses are non-Gaussian, the Laplace Moving Average (LMA) method and a transformed Gaussian approach are studied to model the non-Gaussian responses. The transformed Gaussian approach is adopted for the computation of the upcrossing spectrums. The extreme ship responses are then estimated from the upcrossing spectrums. The standard deviation, zero upcrossing frequency, skewness and kurtosis of responses are needed to compute the upcrossing spectrums. It is shown that the extreme responses computed by the proposed method agree well with those computed by the standard engineering method using the measured responses.

Keywords: Fatigue assessment, extreme response, rainflow, narrow-band approximation, Laplace Moving Average model, transformed Gaussian, zero up-crossing response frequency, significant wave height, safety index, upcrossing spectrum, long term cumulative distribution function, ship routing.

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List of Papers

The doctor thesis includes the following papers:

Paper 1:
Comparison between a fatigue model for voyage planning and measurements of a container vessel
Wengang Mao, Jonas W. Ringsberg, Igor Rychlik, Gaute Storhaug
Published in Proceedings of the 28th International Conference on Ocean, Offshore and Arctic Engineering, May 31 - June 5, 2009, Hawaii, USA, OMAE2009-79235.

Paper 2:
Development of a Fatigue Model Useful in Ship Routing Design
Wengang Mao, Jonas W. Ringsberg, Igor Rychlik, Gaute Storhaug
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Paper 3:
Safety index of fatigue failure for ship structure details
Wengang Mao, Igor Rychlik, Gaute Storhaug.
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Paper 4:
Fatigue damage assessment of container ships concerning wave-induced torsion
Zhiyuan Li, Jonas W. Ringsberg, **Wengang Mao**
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Wengang Mao, Zhiyuan Li, Jonas W. Ringsberg, Igor Rychlik, Thomas Galtier
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Paper 6:
Efficient estimation of extreme ship responses using upcrossing spectrum
Wengang Mao, Igor Rychlik
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Paper 7:
Estimation of Extreme Ship Response
Wengang Mao, Igor Rychlik
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One paper is excluded from the thesis because of the similar topics as Paper 2.

Paper 8:
The effect of whipping/springing on fatigue damage and extreme response of ship structures
Wengang Mao, Jonas W. Ringsberg, Igor Rychlik
Published in Proceedings of the 28th International Conference on Ocean, Offshore and Arctic Engineering, June 6 - 11, 2010, Shanghai, China, OMAE2010-20124.

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Chapter 1
Introduction

Around 90% of the world trade is transported through the international shipping industry. The losses of commercial ships do not only refer to the loss of human life, the ships and their cargoes, but also involve the environmental pollution, the increase of shipping costs due to insurance premiums, and the decrease of the shipping market due to a poor reputation. Therefore, the safety assessment of a commercial ship is the most important issue in the ship industry. The analysis of fatigue strength and ultimate strength of ship structures in today's ship classification society rules, such as *IACS (2006)*, still follows, to a large extent, some empirical relationships.

1.1 Background and Motivation

Ocean-going ships are sailing in waves of different regions. wave-induced loads are caused by the interaction between ship and waves. These can be modeled by a damped spring-mass system, where ships are modeled by a rigid/flexible body. The encountered waves are usually described by the stochastic random processes. The wave-induced loads can force the center of the ship keel to bend upwards and downwards, known as hogging and sagging, respectively, shown in Figure 1.1. The hogging occurs when the crest of the wave is located amidships, while the sagging is caused in the case of the trough of the wave locating amidships. The interlaced hogging and sagging cause repeated loading and unloading to ship structures, leading to fatigue problems on ship construction materials.

Most often, ships are constructed with high tensile strength steel using welding technology. The fatigue damage starts to accumulate in ship structures directly when the ship is launched, because of the wave-induced loads. Actually, fatigue damage is a progressive and stochastic process when a material is subjected to cyclic loadings. Fatigue failure can take place when the maximum stress value is less than the ultimate tensile strength or possibly even below the yield stress limit. Accidents caused by fatigue failure have been documented and researched for over 150 years.

The structural analysis also includes assessment of the yielding strength, buckling strength and ultimate strength. When the structural tensile stress exceeds the "elastic limit (also known as the yield point)" of ship construction material, ship structures start to deform plastically. Further, if the structural stresses increase to an even higher level and reach the ultimate tensile strength, ships may collapse through local failures due to the lack of ultimate strength. Additionally, ship accidents may be caused by the structural buckling because of high compressive stresses. (Accidents due to navigational errors, such as ship grounding, and collision etc., fall outside the scope of current research.) Therefore, the design extreme responses on ship structures should be less than the ultimate strength of the construction material (and the critical buckling stress for the ship structures), in order to keep the integrity and safety of the whole ship structural system. The extreme ship response is referred to as the *T*-year return values of structural stresses, while *T* is often determined according to the design safety level.

Figure 1.1, Vertical 2-node vibration of ship structure

Nowadays, because of the increase of ship size, the optimization of local structural details, and the use of new higher strength materials, the safety assessment of the ship structures according to classification rules may lead to potential risks for the ships. For example, high-frequency vibration (also known as whipping/springing), observed in the full-scale measurements (see *Storhaug (2007)*), is reported to contribute to a large part of the total fatigue. It may also lead to a significant increase of the predicted extreme responses of ship structures. However, classification society rules rarely consider the effect of whipping/springing for safety analysis, due to a lack of experience.

As a consequence, fatigue failures and fractures occur earlier than expected in the vessels. For example, fatigue cracks are observed onboard much earlier than elsewhere even for the well design ships; see *Moe et al. (2005)* and *Storhaug et al. (2007)*. The cracks could be a great threat to the ship safety. As a consequence, special attention is given to the risk and safety margin of the vessels in operation. For ship owners and operators, the economic aspect is of equal importance as safety, and their concern about ship fatigue is related to maintenance, repair costs and reputation. Hence, one important issue to consider ship safety is to assess the fatigue strength of ship structures during design and service period. Meanwhile, ship accidents due to the structural collapse and local buckling are still occasionally happening (see Lloyd's Marine Information Service (LMIS) operated database).

Further, every year large numbers of new ships are launched into the shipping market. Some of the vessels have to change their original design routes due to heavy shipping traffic. Sometimes, these ships may be chosen to travel in more severe sea conditions and experience higher fatigue damage accumulation rates. Moreover, the severe environments may lead to the increase of extreme responses of ship structures during long term sailing. It can cause structural failures due to local ultimate strength and buckling. Both problems could result in a considerable decrease of ship's time of service. This concern is aggravated as the costs for repairs and loss of production increase during the service period.

Moreover, as it is known that the variability of structural stresses on ships is mainly induced by the encountered wave environments, both fatigue analysis and extreme response predictions of ship structures are related to the distribution of the encountered seas. The encountered seas can be modeled as "locally" stationary processes. A stationary sea condition is often modeled by means of linearly interacting Gaussian cosine waves, and for heavy seas, by non-Gaussian second order Stokes waves. There are several approaches to get the information of the wave environments in certain ocean regions, such as measurements from satellites, buoys, and onboard radars. Wave environment data can be also obtained directly from classification rules used in order to guide ship design.

The random wave environments make the structural analysis of ships uncertain. In addition, the properties of ship structures, such as the geometry, surface smoothness, surface coating, residual stress, material grain size and defects and manufacturing processes, can also lead to large uncertainties of the safety assessment. Hence, a reliability-based limit-state design becomes popular for structural design to combine all possible uncertainties.

1.1.1 Fatigue assessment of ship structures

Most often, structural stresses on ships fall within the material elastic range during the service period, and the deformation is also primarily elastic. Fatigue failure of the ship structures usually requires more than 10^4 cycles, known as high-cycle fatigue. Estimation of the high-cycle fatigue accumulation is carried out based on the structural stresses. (Hence, the strain based low-cycle fatigue analysis and fracture mechanics are not used in this thesis.)

For high-cycle fatigue analysis, material behavior is commonly characterized by the relevant *S-N curve*, also known as a *Wöhler curve*, with a log-linear dependence between the number of cycles to failure *N*, and the stress cycle range *S*,

$$\log(N) = \alpha - m\log(S) + e \ , \tag{1}$$

where parameters $\alpha > 0$ and $m \geq 1$ depend on the properties of material, structural details and the stress ratio *R*; with *e* is a random "error". When computing the fatigue damage of welded ship structures, the parameters a, m are usually categorized into different types based on the properties of structural details. They are derived from tests on samples of the material to be characterized (often called *coupons*) where a regular sinusoidal stress is applied by a testing machine which also counts the number of cycles to failure. This process is sometimes known as coupon testing. Each coupon test generates a point on the plot, although in some cases there is a run-out where the time to failure exceeds that which is available for the test. Analysis of fatigue data requires techniques from statistics, especially survival analysis and linear regression.

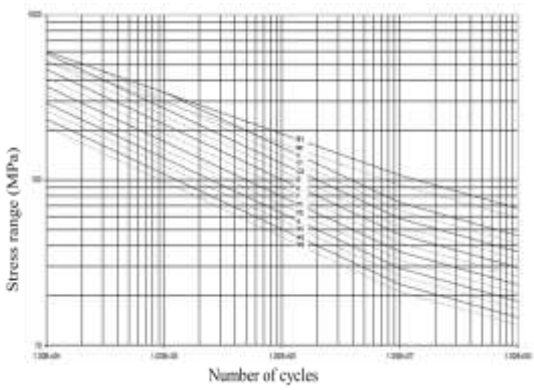

Figure 1.2, S-N curves of different structure types in *DNV (2010)* for fatigue design.

The *S-N* curves with a single slope and two slopes are mostly used in the application of ship industry. The two-slope *S-N* curve is used to consider the fatigue limit of structural details (material). Parameters of the relevant *S-N* curves are usually given in ship classification rules for different ship details (material and structure types). For example, several *S-N* curves used in the DNV guidelines, *DNV (2010)*, are presented in Figure 1.2, where the magnitude of a cyclical stress range (S) is plotted against the logarithmic scale of cycles to failure (N).

Ship structural components are exposed to a complex, often random, sequence of loads when ships are sailing. In order to evaluate the safety level of the components, the stress cycles of the random loads are first extracted using a certain technique. Fatigue damage contributed from each stress cycle can be calculated through the relevant *S-N* curve. Subsequently, the total accumulated fatigue damage is computed by summing the fatigue damages of all stress cycles using a cumulative algorithm, for example a linear Palmgren–Miner's rule, or some other non-linear fatigue accumulation laws. *Fatemi and Yang (1998)* gives a brief review of different fatigue cumulative laws. In the engineering community, the Palmgren–Miner's rule, proposed by *Palmgren (1924)* and *Miner (1945)*, is still widely accepted because of its simple form for applications. The rule, alternatively called Miner's rule or the Palmgren-Miner linear damage hypothesis, states that where there are k different stress magnitudes in a spectrum, S_i $(1 \le i \le k)$, each contributing n_i cycles, then the fatigue damage accumulation D can be estimated by Eq. (2) in combination with the relevant *S-N* curve,

$$D = \sum_{i=1}^{k} \frac{n_i S_i^m}{\alpha}, \tag{2}$$

where D is experimentally found between 0.7 and 2.2 when the failure occurs, but for design purposes D is assumed to be 1; and α ,m are the related S-N curve parameters.

Note that the large effect of mean stress on fatigue damage has been widely studied in literature, for example *Goodman (1919)*, *Smith et al. (1970)*, *Dowling (2004)*, and *Jonhannesson et al. (2005)* etc. It is also reported that the variable amplitude loading sequence has a significant influence on fatigue accumulations; see *Barsom (1976)*, *Van Paepegem and Degrieck (2002)* and *Taheri et al. (2003)*, etc. However, in this thesis, both effects have been omitted neglected for the current fatigue analysis on ship structures.

For fatigue life predictions during ship design, the distribution of stress ranges and the total number of stress cycles N_s are usually used to compute the damage. In this approach, the stress ranges S_j are often divided into M segments from 0 to the maximum stress range S_{max}, i.e. $0 \leq S_{j-1} < S_j \leq S_{max}$ $(1 \leq j \leq M)$. The damage in Eq. (2) is then expressed by

$$D = N_s \sum_{j=1}^{M} \frac{P_j S_j^m}{\alpha}, \tag{3}$$

Here P_j is the probability of the stress ranges that have occurred in the jth segment. The distributions of the stress ranges are usually described by some empirical functions for different types of ships at different locations in the classification society rule, such as *IACS (2006)*. In order to get the empirical distribution function, the stress cycles should be first defined by a certain counting method. The rainflow counting method, proposed by *Matsuishi and Endo (1968)*, is the most frequently used way for fatigue life predictions. Some other methods have also been proposed in literature for defining the cycles, such as the min-Max counting method, the crossing counting method, the positive peak counting method, and the one given in *Holm and de Maré (1988)*, etc. A detailed description of different methods is introduced in, for example, *ASTM (1985)*. The cycle counting methods are also needed in the time-domain fatigue analysis. A brief overview is presented in the following text.

However, for the design of a new type of vessel, the empirical distribution is not available at all. Further, if one wants to estimate the fatigue damage accumulation of a vessel in operation in a specific time T, some more sophisticated methods should be employed for the fatigue analysis. In these cases, the ship operation period is assumed to be composed of a series of stationary sea states. A sea state is used to describe the general condition of the wave elevation surface. It is characterized by the statistical information, including the significant wave height H_s, wave period T_p, and power spectrum. The sea state is usually assessed by some instruments like buoys, wave radar or satellites. The sea states usually vary in time with respect to the wind or swell conditions. For the computation of fatigue damage, ship responses at each sea state can be either computed by a numerical analysis, or measured by the strain sensors. Consequently, fatigue damage accumulation at different sea states can be estimated by, for example, the time-domain fatigue analysis or spectral fatigue analysis.

Time-domain fatigue analysis

In the case when the stress history in time T is available (measured or computed), the damage accumulation can be estimated by Eq. (2), and extrapolated to a longer term period. This approach is often called the time-domain fatigue analysis. The stress cycles in Eq. (2) are counted from the local maxima (peaks) and minima (troughs) of the stress history by a cycle counting method.

The simplest counting method is the so-called min-Max (Max-min) counting method, where the local maximum is paired with the preceding local minimum. The stress cycles in this method only consider the effect of local stresses, but ignore the global effect including large cycles. Therefore, this method is not capable of estimating the risk of fatigue failure, since it gives non-conservative (too small) fatigue damages.

The most frequently used rainflow counting method is developed on the hysteretic properties of material, where the cyclic stress-strain curves form hysteretic loops. The local maxima are represented by tops of the loops, while local minima by bottoms of the loops. The rainflow method is to identify the local minimum which should be paired with a local maximum to form a hysteretic loop. It is believed to give the most “accurate” fatigue life predictions. This conclusion is proven, for example, by *Dowling (1972)* and *Watson and Dabell (1975)*, using *S-N* curves regressed from experiments under constant amplitude loads. The original definition of the rainflow counting algorithm is described in the next section for completeness. The definition has been developed for convient applications, for example the so-called 4-points algorithm proposed by *de Jonge (1982)* and the 3-points algorithm introduced in *ASTM (1985)*. *Rychlik (1987)* proposes a non-recursive mathematical definition, enabling closed-form computations from the statistical properties of the load signal. It can be used to consider a more general case of continuous loads with an infinite number of cycles. This mathematical definition is also briefly presented in the next section, and applied in this thesis for time domain fatigue estimation using the Matlab Toolbox – WAFO *(WAFO-group 2000)*.

Another approach to define the stress cycles can be taken by the crossing counting method, proposed in *Rychlik (1993a)*. This method gives priority to large stress cycles in the stress history. The peaks and troughs are paired into cycles, leading to the maximum estimation of the accumulated fatigue damage. Hence, it is an upper bound for the rainflow damage. In comparison with the rainflow counting method, the damage computed from the min-Max counting method is the lower bound of the rainflow damage, while the crossing counting method gives the upper bound of the rainflow damage. This is used by *Tovo (2002)* to predict the rainflow damage using the irregularity factor of load.

The cycle ranges obtained from the counting methods are usually described by means of probability distribution. Consequently, the fatigue damage can be computed by Eq. (3). For the fatigue design of ship structures, all possible sea conditions in the wave scatter diagram (e.g. DNV (2007)) should be considered. The computation of stresses for the ship at all different sea states is extremely time-consuming. Therefore, an alternative approach is to use the spectral fatigue analysis, where ship stresses are assumed to be Gaussian. Hence, for each sea state the cdf of rainflow cycle ranges is approximated by Rayleigh distribution. The range distribution in the design life is obtained by mixing the distribution of each sea state using the long term cdf of sea states, see DNV (2010). In this case, the Response Amplitude Operators (RAOs), also known as transfer functions and computed by a linear numerical analysis in frequency domain, are used to determine the effect of a sea state upon ship responses. The response spectrums are then computed combing the transfer functions and encountered sea states. The parameter in the Rayleigh distribution is computed using the response spectrum.

Spectral fatigue analysis in frequency domain

In the early 1960’s, when definition of the rainflow counting method was not available, Bendat (1964) proposed to approximate fatigue damage for a narrow-band process by the corresponding upcrossing spectrum. This method is well applicable for the symmetric loads. For the zero mean stationary Gaussian loads, the formula of fatigue damage by Bendat (1964) is simple expressed by the first and second order spectral moments of the Gaussian loads, also known as the narrow-band approximation (NBA). The detailed derivation of narrow-band approximation is presented in the following section. It is proved that NBA is an upper bound for the expected rainflow damage. For broad-band processes, see Figure 1.3 for illustration, the NBA may lead to a severe overestimation of the expected rainflow damage. Hence, several effective methods have been proposed for the Gaussian loads.

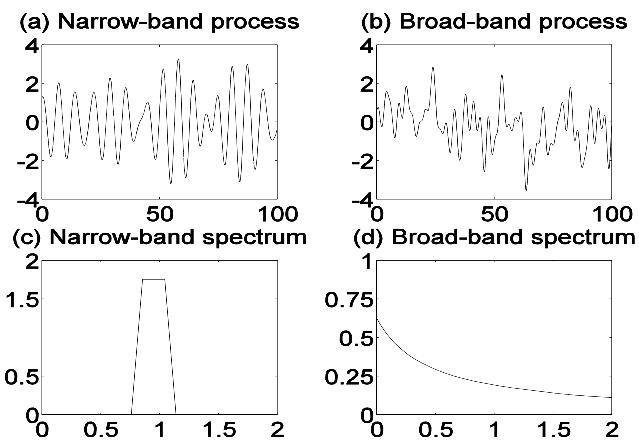

Figure 1.3, Examples of narrow-band and broad-band processes

For a very broad-band process, perhaps the simplest way to reduce conservatism is to split the spectrum into two different components, Low-Frequency (LF) and High-Frequency (HF) loads. Then narrow-band approximation is still used to compute damage induced from both LF and HF components. The total fatigue is the summation of the contributed fatigue of the two components. This approximation is closely related to the approximation proposed by *Sakai and Okamura (1995)*, and more recently investigated by *Olagnon and Guédé (2008)*. This method is applicable for the loads of special spectrum, such as the bimodal spectrum where the LF part represents the slowly varying loads while the HF part is the oscillations superimposed around the LF components. However, as reported in *Benasciutti and Tovo (2007)*, this approach may give non-conservative predictions when the HF part contains too much energy. Another approach, introduced by *Jiao and Moan (1990)*, proposes to add the interaction term between the LF and HF components, using the envelope process of the fast component. This method is also illustrated to be quite accurate especially for large LF contributions, such as the mooring lines, see *Gao and Moan (2007)*.

Alternatively, various models have been proposed for considering the properties of broad-band processes, adding a correction factor on the narrow-band approximation, such as *Wirsching and Light (1980)*, *Tovo (2002)* and *Benasciutti (2004)* etc. The correction factor is somehow related to the so-called spectral bandwidth parameter. The parameter is defined as the ratio of the mean level upcrossing intensity to the intensity of local maxima. It is used to reflect the spread of energy in the power spectral density. The spectral moments of the stationary Gaussian processes are usually used for computing the parameter. Since the computation of the second and higher spectral moments is sensitive to the choice of cut-frequency of responses, the approximation using a single lower spectral moment is derived for Gaussian loads by *Lutes and Larsen (1990)*. A detailed comparison of these methods for the Gaussian loads with different spectra is carried out in *Bengtsson et al. (2009)*.

The real ship responses are rarely Gaussian. For non-Gaussian stresses, the spectrum alone does not define the distribution of processes, and hence, some additional information is needed for the cdf of cycle ranges. If, for example, skewness and kurtosis are known, the transformed Gaussian model can be used, see *Winterstein (1985 and 1988)*, leading to the stress amplitude being Hermite polynomials of Rayleigh distribution. Alternatively, using Laplace Moving Average (LMA) method, the upcrossing spectrum can be computed, and then the expected damage is bounded by means of the generalized NBA, see *Rychlik et al. (1997)*.

Uncertainties of fatigue life predictions

The fatigue life of a structural detail is greatly influenced by a number of components and material dependent factors, such as geometry, size of the structure, surface smoothness, surface coating, residual stress, material grain size and defects. The nature of the load processes is also important for fatigue accumulations. The complex dependence between these factors and fatigue life leads to great uncertainties on the prediction of structural fatigue life. In actual fact, the results from fatigue life tests also exhibit a considerable scatter, even for controlled laboratory experiments. For instance, in Figure 1.4, results of constant amplitude experiments are marked by pluses. One can see that the *S*-*N* relation for the constant amplitude load would give the same m but also a higher value of the parameter α. It indicates that using α in Eq. (1) from the constant amplitude experiments will give some (non-conservative) bias.

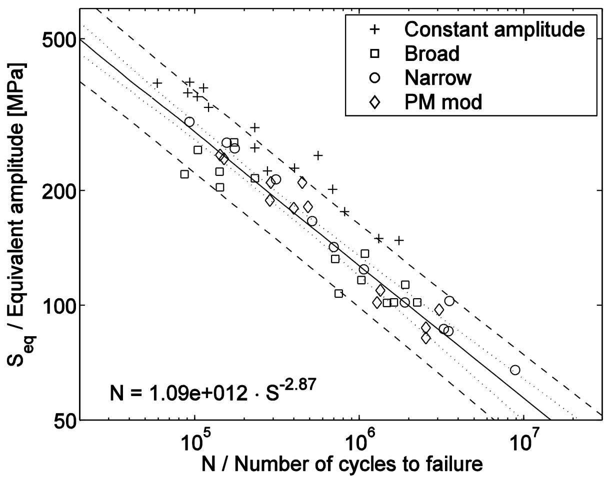

Figure 1.4, S-N curve estimated from variable amplitude tests using broad-banded, narrow-banded and Pierson-Moskowitz spectra compared with constant amplitude tests (*Agerskov, 2000*).

Although the simple Palmgren-Miner cumulative rule is widely used in the real applications, it often gives a poor prediction and contains large uncertainties, shown in *Johannesson et al. (2005)*, so that it is too simple to fully describe the fatigue accumulation process. Ship responses are usually computed by a numerical analysis for fatigue design of ship structures. However, large deviations are reported in *Storhauge et al. (2003)* due to different numerical codes. Even though the responses are obtained from measurements, the fatigue damage analysis for specific locations on ships is also uncertain because the stress concentration factor (SCF) is not easily determined for the computation of local stresses. Further, the external wave environments should be correctly described for the reliable computation of damages. The uncertainties may be caused by the description of the encountered sea conditions. For example, it has been shown that the distribution of H_s given in the classification rule is significantly different from that obtained from the onboard measurements. In general, some of these uncertainties can be described by random variables. Then the simple Cornell's safety index can be used to assess the risk of fatigue failure, see for example *Bengtsson et al. (2009)*.

1.1.2 Extreme response prediction of ship structures

For ship structural design, the computation of extreme stresses is often needed for the evaluation of a ship's safety levels. The corresponding extreme stresses should be less than the ultimate strength of ship structures. If long records of stress measurements are available and stationary shipping can be assumed, certain standard statistical methods for predicting the extreme responses could be employed, see *DNV (2007)*, and more details in *Ochi (1981)*. The most commonly used method is to fit the long term cumulative distribution function (cdf) of peaks in the stress history. Then, a suitably chosen quantile of the fitted cdf determines the design extreme stress.Most often a two parameter Weibull distribution is used to fit the long term cdf.

The second approach is to extract maxima in blocks of measurements, e.g. to find hourly and yearly maximums of the stress history, and then fit Gumbel or the Generalized Extreme Value distribution (GEV) to the block maxima. The third one is the Peak Over Threshold (POT) method, which is a systematic way of analyzing the tails of a distribution by means of exceedances over some high levels. In the standard version, POT employs the so called Generalized Pareto Distribution (GPD) to model the tails of responses.

Another popular approach for the computation of extreme responses is using the upcrossing spectrum, here alled Rice's method. Most often, Rice's method and the long term cdf fitting method give almost identical results of extreme ship responses if the observed upcrossing spectrums are applied. However, Rice's method is particularly convenient if the upcrossing spectrum of ship responses can be computed by an analytical approach. An efficient computation of extreme responses for oil rigs has been presented in *Naess and Karlsen (2004)* using the upcrossing spectrums from a numerical analysis. If ship responses at each stationary sea state are assumed to be Gaussian, Rice's formula (*Rice (1944, 1945)*) can be used to compute the corresponding upcrossing spectrum. However, due to the complex interaction between ship structure and applied waves, ship responses are usually regarded as non-Gaussian processes in particular under large sea states. The mathematical modeling of non-Gaussian loads is widely investigated in the literature, *e.g.*, for quadratic responses see *Jensen and Pedersen (1979)*, *Naess (1985), Machado (2003)* and *Butler et al. (2009).*

The so-called Laplace Moving Average (LMA) model in *Kotz et al. (2001)*, can model the upcrossing spectrum of non-Gaussian responses often encountered in offshore and automotive applications, see *Åberg et al. (2009)*. The upcrossing spectrums of ship stresses computed by LMA agree well with observed upcrossing spectrums; see *Paper 3*. However, the complicated computation of the upcrossing spectrum by LMA may limit its applications. The transformed Gaussian approaches are particularly useful in modeling the non-Gaussian ship responses, and subsequently the corresponding upcrossing spectrum can easily be computed for extreme predictions, see *the last two papers*.

Finally, the long term distribution of encountered sea conditions (sea states) is needed to compute ship responses when no measurement is available. The computation of all the non-Gaussian ship responses using nonlinear hydrodynamic codes is extremely time-consuming due to the complex interaction between ship structures and applied waves. Most often, the variability of sea states (H_s, T_p) is described by the environmental contour line proposed by *Winterstein et al. (1993)*. This method captures the long term distribution of encountered sea states by identifying the most critical sea state for the estimation of extreme responses.

1.1.3 Descriptions of wave environments

For both fatigue assessment and extreme predictions of ship structures, ocean waves are described as a sequence of stationary periods (sea states). The analysis is then carried out for each sea state, where the elevation of wave surface is described by a random process. A stationary sea state can last from 20 minutes to several hours. It is mainly characterized by the significant wave height H_s and wave period T_p. Due to its importance for both fatigue and extreme analysis of ship structures, the variability of sea environments mainly H_s has been extensively studied in literature.

The wave scatter (H_s, T_p) diagram and fitted distributions of sea states recommended by classification societies, for example in *DNV (2007)*, may be one of the most convenient sources (and most often used in engineering practice) for guiding the ship design. The wave diagram in classification rules is based on visual observations (the Global Wave Statistics Atlas, BMT (*Hogben et al. (1986)*) collected by officers onboard of sailing ships. The Global Wave Statistics Atlas includes monthly averages, so it is possible to describe the variation along specific shipping routes, or even the variation of seasonal changes, in average. However, more complicated wave models are needed for specific applications, for example, ship routing design.

Some statistical wave models have already been developed using the wave data measured from satellites and buoys. The wave models are able to accurately describe the distribution of waves. For example, such a Spatio-temporal model of H_s has been proposed in *Baxevani et al. (2005)* and *Baxevani et al. (2009)*. This model can consider the correlation between geographical locations and time of the year of interest for shipping; see *Baxevani and Rychlik (2007)*. The model can be used for analytical computations or simply provide simulations of encountered H_s along shipping routes. A brief description of this spatio-temporal wave model is also presented in the following section. Further, wave radars have been installed in some ships to measure the encountered significant wave height H_s along their sailing routes. However, those measurements are often unreliable due to complexity of the measuring problems as well as needs for calibrations.

Since different measurement techniques are used and mostly because of different sampling schemes, the cdf of H_s obtained from the above sources may deviate greatly. For example, Figure 1.5 presents the empirical probability density function (pdf) of H_s

recommended by *DNV (2007)*, together with the pdf of H_s measured onboard (left plot), and with the distribution of H_s simulated from the spatio-temporal model proposed by *Baxevani et al. (2009)* (right plot). It is shown that onboard measurements (along the North Altantic routes) and the spatio-temporal model contain much more moderate seas with H_s from 2 to 6m, which contribute most of the fatigue damage during a ship's service period. But the probability of large H_s simulated from the spatio-temporal model seems closer to that recommended by *DNV (2007)*. It may lead to a similar result of extreme analysis. Further, large storms are less probable to happen according to the onboard measurements.

The probability of large H_s obtained from the onboard measurements differs significantly from that obtained from the other two approaches. This may be caused by the routing system installed in the measured ship. The routing system can help captains to avoid big storms. Another possible reason of such a difference is due to the limited time of measurements (0.5 year). However, all the sources of wave environments have been applied to assess the safety level of ship structures in the appended papers.

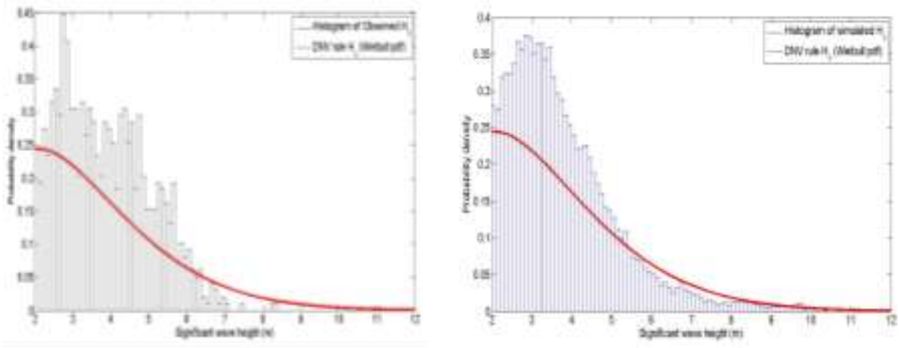

Figure 1.5, probability density function of H_s from different approaches.

1.2 Objective and Scope of the work

The objective of this thesis is to establish a simple fatigue model considering the effect of high-frequency responses, such as whipping/spinging, and propose an efficient method for the extreme response prediction of ship structures.

The fatigue model should be accurate and simple enough for the applications of both fatigue design of ship structures and ship routing design with respect to the minimum fatigue accumulation. The model should be capable of considering the uncertainties caused by, for example, *S-N* curves and environment loads. The proposed fatigue model should be validated by the rainflow counting method using the full-scale measurements of a 2800 TEU container vessel operating in the North Atlantic. Further, when no measurement is available, this model should be able to assess the fatigue damage using a simple numerical analysis.

Ship responses are often regarded to be non-Gaussian, due to the complex interaction between a ship and waves. With the method for extreme response prediction, it should be possible to consider the statistical property of such non-Gaussian responses, for example, skewness and kurtosis. The upcrossing spectrum should be easily and accurately computed using limited information, such as the statistical property of ship responses, wave environments, etc. The extreme ship responses predicted with this method should be validated by those computed using the standard statistical approaches. Moreover, the method should be easily applied to predict the extreme ship responses of other types of vessels using the responses from either measurements or numerical computations.

Finally, since both fatigue assessment and extreme prediction of ship structures greatly rely on the external wave environments, the proposed methods in the thesis should make it possible to estimate the risk level of ship structures and give reasonable estimates for various sea conditions.

The long term objective in the research group is to develop a robust code for assessing ship safety for the ship routing design, which can consider the fatigue accumulation and predict extreme responses of ship structures. Hence, the work presented in this thesis is actually a preliminary investigation in the achievement of our long term objective.

The background and motivation has previouly been covered in this chapter. The remaining parts of the thesis are arranged as follows:

- Chapter 2 presents some basic theories and models which serve as the theoretical background for carring out the research work of my PhD study. These theories and models are provided for either statistical or engineering readers, in order to better understand the detailed contents of the thesis.
- In Chapter 3, the summary of the finished work in this thesis is briefly described. The work of this thesis is actually composed of 7 papers. The summary of each paper helps to distinguish topics and contents in different papers.
- Chapter 4 lists contributions and major findings of the thesis, followed by some suggestions for future work.
- Finally, all the papers are collected in the Appendix. There are 2 published journal papers, 3conference papers, as well as 2 submitted manuscripts.

Chapter 2

Basic theories and models

This chapter briefly describes some preliminary techniques and theories, as the basis of the work in this thesis. The first two subsections deal with the most important methods for fatigue analysis on ship structures, i.e. the Rainflow counting method (time domain analysis) and the so-called narrow-band approximation (NBA) (frequency domain analysis). Sections 2.3 and 2.4 describe the numerical computation and mathematical modeling of non-Gaussian ship responses. The last subsection briefly introduces the established spatio-temporal wave model used in this thesis.

2.1 Rainflow counting method

Rainflow cycle counting was first introduced by *Matsuishi and Endo (1968)*. Now it is standardized as several counting algorithms published in *ASTM (2005)*.

The original version, also known as the pagoda-roof method, is shortly described as follows. Suppose that a time history of stress is composed of a sequence of peaks and troughs. The time history is turned clockwise 90° (earliest time to the top), and then it forms a series of pagoda roofs, shown in Figure 2.1. Water is assumed to fall from the top of a roof structure. Water flows downward following some general rules described below.

- The rainflow starts at a trough (or peak), and flows down the pagoda roofs until it reaches a more negative trough (or a more positive peak) than the trough (or peak), from which the rainflow starts.
- The rainflow stops when it encounters another rainflow which flows down from the previous roof.
- The rainflow terminated at the end of the time history.
- New rainflow will not start until the current rainflow is stopped.
- Each rainflow path forms a half-cycle, and the horizontal length of the path is considered as that stress range.
- Trough-generated half-cycle will match a peak-generated half-cycle to form a whole cycle.

For example, Figure 2.1 shows that the rainflow starts from A (trough), B (peak), C(trough), and so on, respectively. The first rainflow (starts at A) drops down at B and stops at D, because the following trough E is more negative than A. Hence, a half cycle of A-B-D is identified. The rainflow starting from C stops at b since it meets the previous flow, then C-b forms another half cycle. There are a total of 8 half-cycles. Besides the previous two half cycles, the other formed half-cycles are B-C, D-E, E-F, F-G-I, G-H, H-g. Further, B-C and C-b (also G-H and H-g) forms a whole cycle.

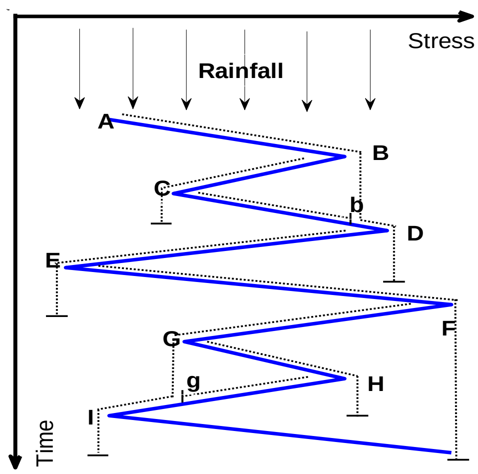

Figure 2.1, Rainflow cycle counting method

In this thesis, an alternative mathematical definition of the rainflow counting method proposed by *Rychlik (1987)* are employed. The method is more convenient for the statistical analysis of rainflow ranges.

For any measured stress (for example a time series of stresses), each maximum of the stress signal, v_i, is paired with one particular local minimum u_i^{rfc}. The pair, (u_i^{rfc}, v_i), is called the rainflow cycle, and the cycle stress range, $S_i = v_i - u_i^{\mathrm{rfc}}$, is then applicable for fatigue analysis. The corresponding minimum of the cycle, u_i^{rfc}, is determined as follows:

- From the i-th local maximum v_i, one determines the lowest values, u_i^{back} and $u_i^{forward}$, respectively, in backward and forward directions between the time point of local maximum v_i, and the nearest crossing points of level v_i along the time series of stress in the left-hand plot of Figure 2.2.
- The larger value of those two points, denoted by u_i^{rfc}, is the rainflow minimum paired with v_i, i.e. u_i^{rfc} is the least drop before reaching the value v_i again between both sides. In the situation of Figure 2.2 (left-hand plot), $u_i^{rfc} = u_i^{forward}$.
- Thus, the i-th rainflow pair is (u_i^{rfc}, v_i), and S_i is the stress range of this rainflow cycle.

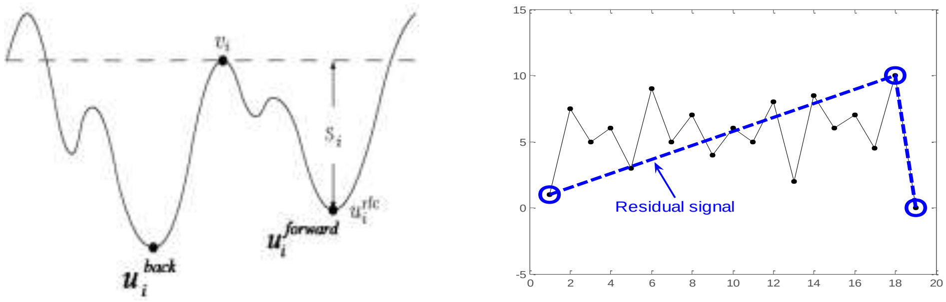

Figure 2.2, **(Left):** definition of a rainflow cycle;   **(Right):** residual signal after rainflow counting

Note that for some local maxima the corresponding rainflow minima could lie outside the measured or caring load sequence. In such situations, the incomplete rainflow cycles constitute the so called residual (see the dashed lines in the right-hand plot of Figure 2.2) and have to be handled separately. In this approach, we assume that, in the residual, the maxima form cycles with the preceding minima.

2.2 Narrow-band approximation for fatigue damage

For a random load in time T, the stress cycle range S_i is a random variable, and thus the damage D_T is also a random variable. The related fatigue failure criterion is reformulated so that $E[D_T] = 1$. The expected damage can be computed if the distribution of cycle ranges and intensity of cycles are known. Here, the distribution describes variability of the range of a cycle taken at random. It can be estimated if the measurement of stresses is available. The distribution can also be computed for special classes of loads, for example Markov loads. For the very important case of Gaussian loads, several approximations were proposed in literature. Maybe the most complex one is the so-called Markov method introduced in *Frendahl and Rychlik (1993)*. The accuracy of this method is widely discussed in *Lindgren and Broberg (2004)*. However, simpler approximation does exist. The most important analysis is the narrow-band method proposed by *Bendat (1964)*, where the expected fatigue damage during the time interval *[0,T]* under the symmetric load is estimated in Eq.(4),

$$D_T^{nb} = \frac{1}{\alpha}\int_0^{+\infty} 2m(2u)^{m-1}E[N_T^+(u)]du, \tag{4}$$

where α, m are parameters of the relevant *S-N* curve, and $\mathrm{E}[N_T^+(\mathrm{u})]$ is the expected upcrossing number of level u in the time interval *[0, T]*. Here, the probability of the cycle ranges is approximated viz.

$$P(S_i > s) \approx E[N^+(s)]/E[N^+(0)]. \tag{5}$$

It is reported in Rychlik (1993b) that $E[D_T] \le D_T^{nb}$. If the loads *x(t)* is a stationary Gaussian process, then by Rice's formula, see Rice (1944, 1945), the expected upcrossing intensity of level u ($E[N^+(u)] = E[N_T^+(u)]/T$ for stationary process), is given as follows:

$$E[N^+(u)] = \frac{1}{2\pi}\sqrt{\frac{Var(\dot{x}(0))}{Var(x(0))}}\exp\left[-\frac{u^2}{2Var(x(0))}\right] = \frac{1}{2\pi}\sqrt{\lambda_2/\lambda_0}\,\mathrm{e}^{-\frac{u^2}{2\lambda_0}}, \tag{6}$$

where λ_0 and λ_2 are, respectively, the zero and second-order spectral moments of the stress *x(t)*. If one denotes the spectrum of response stress *x(t)* as *S(ω)*, then the corresponding spectral moments are computed as $\lambda_i = \int_0^{+\infty}\omega^i S(\omega)d\omega$. Combining Eq. (5) and (6) gives the well known fact that the narrow-band method approximates the cdf of cycle ranges by a Rayleigh distribution viz. $S_i \approx \sqrt{\lambda_0}R$, where the probability density function of the random variable R is $f_R(r) = re^{-\frac{r^2}{2}}$.

In general, the response spectrum can be obtained by the frequency domain analysis for relevant structures. The narrow-band approximation in Eq. (4) for a stationary Gaussian stress process is given by

$$D_T^{nb} = \frac{1}{\alpha}Tf_z h_s^m 2^{-m/2}\Gamma(1+\mathrm{m}/2), \tag{7}$$

where *Γ(x)* is the gamma function, the so-called significant response h_s is 4 times the standard deviation of stress $x(t)$, and the zero upcrossing response f_z as well as the significant response height h_s for a Gaussian stress process can be computed through the spectral moments of the (response) stress $x(t)$ in Eq. (8); for a detailed discussion, see Rychlik (1993b),

$$h_s = 4\sqrt{\lambda_0}\ , \qquad f_z = \frac{1}{2\pi}\sqrt{\lambda_2/\lambda_0} \tag{8}$$

This model in Eqs (7 and 8), also known as the Narrow-Band Approximation (NBA), is an upper bound of the rainflow damage. It is close for the narrow-band stationary Gaussian load. (Stationary Gaussian load is uniquely defined by load spectrum and mean value.)

However, the response process is not always stationary through the whole period *T*, such as 1 year. In offshore applications, it is common practice to divide the whole process into many stationary periods of length t_i. Hence, the expected upcrossing of level u in the whole time interval $[0,T]$ is the summation of the expected upcrossing of all these stationary periods, expressed thus:

$$E[N_T^+(u)] = \sum_i E[N_{t_i}^+(u)] = \sum_i t_i E[N_i^+(u)],$$

in which $N_{t_i}^{+}(u)$ is the upcrossing number of level u during a stationary time period of length t_i, and $\mathrm{E}[N_i^{+}(u)]$ is the upcrossing intensity (i.e. $t_i = 1$). Sometimes, $E[N_T^{+}(u)]$ computed with this approach is not unimodal and symmetrical, hence *Bendat*'s model in Eq. (4) is not appreciated. However, there is a generalization of the narrow-band method for general spectrum, see *Rychlik (1993b)*. These problems were further discussed in *Bogsjö and Rychlik (2007)* for vehicle fatigue analysis.

2.3 Analysis of hydrodynamic loads

If a ship's hull is assumed to be a rigid body, its dynamic response when operating in the ocean can be computed by the spring-mass system as

$$(\boldsymbol{M} + \boldsymbol{A})\ddot{\boldsymbol{X}}(\mathrm{t}) + \boldsymbol{D}\dot{\boldsymbol{X}}(\mathrm{t}) + \boldsymbol{C}\boldsymbol{X}(\mathrm{t}) = \boldsymbol{F_h} + \boldsymbol{F_d} + \boldsymbol{F_g}\,, \tag{9}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{A}$ is the added mass, $\boldsymbol{D}$ and $\boldsymbol{C}$ are the coefficients of damping and stiffness, respectively, and $\boldsymbol{X}$ denotes the displacement of ship hull element nodes. On the right hand side of Eq. (9), $\boldsymbol{F}_h$ represents the hydrodynamic wave excitation force by the incoming waves and the hydrostatic restoring force. $\boldsymbol{F}_d$ is the diffraction force. $\boldsymbol{F}_g$ is the inertial force due to the gravity acceleration. Wave elevations, known as a random field, are usually described by the sum of a series of harmonic waves as follows,

$$\zeta = \sum_{i=1}^{N} \zeta_i \sin(\omega_i t - k_i x + \varepsilon_i)\,, \tag{10}$$

where ζ_i is the wave amplitude of each harmonic wave with the frequency ω_i, k_i is the wave number, and ε_i is the phase angle. If the sea state is described by some classical wave spectrum $S(\omega)$, for example Pierson-Moskowitz or JONSWAP, the wave amplitude of each regular wave is $\zeta_i = \sqrt{2\boldsymbol{S}(\omega_i)\Delta\omega}$. The wave phase ε_i is then chosen as a random variable to model the random wave elevations. If the wave amplitude is very small, the Froude-Krylov and hydrostatic pressure can be integrated over the mean free surface and mean wetted surface. This linear approach is a good approximation when the ship is operating in relatively calm waters with small motions. In this paper, the large storm phenomena should be studied to predict the extreme response. The assumption of the mean wetted surface may make the analysis too crude. Thus the exact wetted surface should be used for computing the correct wave excitation force and restoring force. Hence, in the time domain analysis, the relative motion in Eq. (9) could be computed to determine the wetted surface for each time step. Further, when a ship operates with a high forward speed, the effect of diffraction and radiation cannot be neglected. In our investigation, a hydrodynamic code WASIM using a 3D panel model is chosen for running the simulations. The nonlinear terms in WASIM for our simulations can also include the quadratic terms in the Bernoulli equation and quadratic roll damping.

After getting the hydrodynamic loads for each time step, structural responses can be computed using either the FEM method or a simplified beam model calculation. In this paper, a 4400 TEU container ship will be used for investigation. And the location for the computation is located in the deck area of the mid-section. Structure analysis is implemented using a vertical bending moment and sectional modulus, assuming a stress concentration factor 2.

2.4 Transformed Gaussian method

wave-induced loads are often known as non-Gaussian processes. They can be modeled by a nonlinear damped spring-mass system, loaded by the linear (Airy) waves or nonlinear (Stocks) waves. Structural stresses can be computed by, for example, a finite element method applying the wave loads. In this thesis, a linear beam model of ship structures is employed in order to compute the structural stresses. Due to the importance for ship safety assessment, the mathematical modeling of the non-Gaussian responses (hydrodynamic loads $X(t)$) is widely studied in literature.

For example, the so-called Laplace Moving Average (LMA) approach has been proposed to model non-Gaussian processes for the computation of fatigue damages, see *Åberg et al. (2009)*. In *paper 5*, the LMA approach has been used for modeling the non-Gaussian ship responses, and the corresponding upcrossing spectrum is also computed. It is shown that the computed upcrossing spectrum agrees well with the observed upcrossing spectrums. The LMA model requires knowledge of power spectrum, skewness and kurtosis of the ship responses. However, a limitation of the LMA model, similarly as for the second order Stokes waves, is that the joint pdf of the response and its derivative is not available in an analytical form. (The pdf is defined in the frequency domain by its characteristic function and has to be computed using numerical methods.)

The transformed Gaussian model proposed in *Winterstein et al. (1994)*, has been shown to provide good accuracy in representing a wide range of non-linear behaviors. It is also adopted for modeling the non-Gaussian ship responses in the thesis. The transformation is defined by the third order Hermite polynomial, which is calibrated so that the variance, skewness and kurtosis of the transformed Gaussian model match the corresponding moments of the response *X(t)*, viz. the mean value m, standard deviation σ_X, skewness $\alpha_3 = E[X(t)^3]/\sigma_X^3$, and kurtosis $\alpha_4 = E[X(t)^4]/\sigma_X^4$ of the response.

In the following, let the parameters of the ship responses at a sea state W, i.e. m, σ_X, $\sigma_{\dot{X}}$, α_3, α_4, collect in a vector Θ. Given the parameter vector, $\Theta(m, \sigma_X, \sigma_{\dot{X}}, \alpha_3, \alpha_4)$, the transformed Gaussian process is defined by

$$X(t) = G(Y(t)) = \kappa\sigma_X \cdot \left[H_1(Y(t)) + c_2 H_2(Y(t)) + c_3 H_3(Y(t))\right], \qquad (11)$$

where, H_i are Hermite polynomials and Y is a standard Gaussian process (in what follows, the mean stress $m = 0$). The other parameters proposed by *Winterstein et al. (1994)* in Eq. (11) are

$$\kappa = \frac{1}{\sqrt{1+2c_2^2+6c_3^2}};$$

$$c_2 = \frac{\alpha_3}{6} \cdot \frac{1-0.015|\alpha_3|+0.3\alpha_3^2}{1+0.2(\alpha_4-3)};$$

$$c_3 = 0.1c_4\left[(1+1.25(\alpha_4-3))^{1/3}-1\right];$$

$$c_4 = \left(\frac{1-1.43\alpha_3^2}{\alpha_4-3}\right)^{1-0.1\alpha_4^{0.8}}. \tag{12}$$

Let G^{-1} be the inverse function of G, then $Y(t) = G^{-1}(X(t))$. Subsequently, the uncrossing frequency at a sea state W can be computed using Rice's formula viz.

$$\mu^+(x|\Theta) = f_z \exp\left(-\frac{G^{-1}(x)^2}{2}\right), \qquad f_z = \frac{1}{2\pi}\frac{\sigma_{\dot{X}}}{\sigma_X}. \tag{13}$$

Note that in some cases the cubic term cannot sufficiently ensure that the Hermite transformation in Eq. (11) remains monotone for all response levels. Therefore, for certain sea states of responses with relatively low kurtosis, the method may fail to determine the transformation for the high response levels. Some modifications of the transformation are needed for such cases. However, this is a small problem in comparison to the advantage obtained by having an analytical expression for the upcrossing frequency $\mu^+(x|\Theta)$.

Besides the cubic Hermite polynomial transformation proposed by *Winterstein (1985 and 1988)* and *Winterstein et al. (1994)*, other transformations have been proposed in the literature, for example *Ochi and Ahn (1994)* used a monotonic exponential function. In *Sarkani et al. (1994)* and *Kihl et al. (1995)*, a power law model is used to define the transformation. All the above approaches are defined as functions of skewness and kurtosis of the non-Gaussian process. Alternatively, a non-parametric definition of the transformation is also proposed by *Rychlik et al. (1997)* for modeling the ocean waves.

2.5 Spatio-temporal wave model

For offshore engineering, the significant wave height H_s is the most important parameter to describe wave environments. The distribution of H_s along shipping routes is needed for estimating the expected fatigue accumulation during a long term period.

As reported in Baxevani et al. (2005), the significant wave height at position $\boldsymbol{p}$ and time t is accurately modeled by means of a lognormal cumulative distribution function (cdf). Let $X(\boldsymbol{p}, t) = ln(H_s(\boldsymbol{p}, t))$ denote a field of logarithms of significant wave height that evolves in time. For a fixed t, the local field $X(\boldsymbol{p},t)$ is assumed to be homogeneous Gaussian with covariance changes for the location $\boldsymbol{p}$. The Gaussian field $X(\boldsymbol{p}, t)$ is assumed to have a mean that varies annually due to the periodicity of the climate. In the model, the mean value of the Gaussian field is assumed as follows

$$\mu(t) = E[X(\boldsymbol{p}, t)] = \beta_0 + \beta_1 \cos(\phi t) + \beta_2 \cos(\phi t) + \alpha t \tag{14}$$

where $\phi = 2\pi / 365.2$ is chosen to give an annual cycle for time in days. The mean values of the model can be computed from the satellite measurements,

Suppose t_0 be the starting date of a voyage, $\boldsymbol{p}(t) = (x(t), y(t)), [t_0, t_1]$, the planned route, while $v(t) = (v_x(t), v_y(t))$ the velocity a ship will move with. For a route let $z(t) = X(\boldsymbol{p}(t), t)$ be the encountered logarithms of H_s. (The encountered significant wave height is $H_s(t) = exp(z(t))$.) Obviously it will be different for $\boldsymbol{p}$ close to the coast and for $\boldsymbol{p}$ in the mid-ocean. Hence, the encountered process $z(t)$ will be Gaussian but non-stationary.

In principle, the mean value and variance of the Gaussian field are needed in order to compute the distribution of H_s along the route. The covariance structure is needed if the variance of fatigue damage is required, for example, in the computation of safety index. In general, the data from both satellites and buoys are necessary to get the parameters of the covariance structure in the model.

A spatio-temporal model, e.g. the median value of H_s in February and August, is shown in Figure 2.4. A further description and validation of this model can be referred to Baxevani et al. (2007) and Baxevani et al. (2009). Additionally, Baxevani and Rychlik (2007) present a simple example, applying this model to estimate fatigue damage of a ship sailing in the North Atlantic.

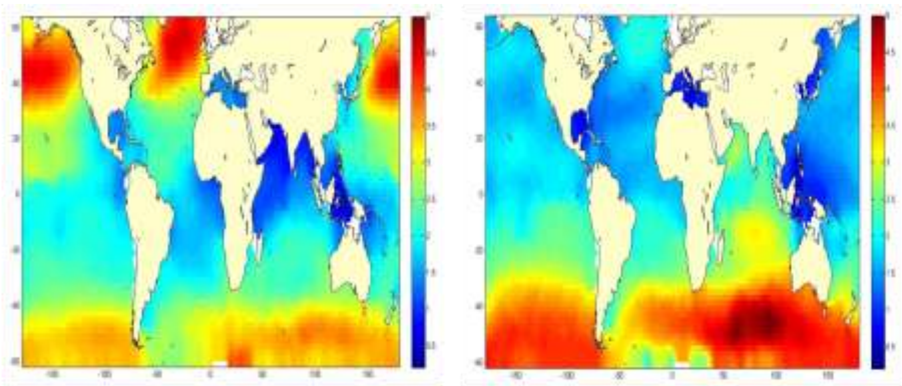

Figure 2.4, the median value of H_s (meters) in February (**left**) and in August (**right**).

Chapter 3
Summary of papers

This thesis is composed of 7 papers. The first two papers deal with the development of a fatigue model. Based on the proposed fatigue model, the third paper performs a reliability and risk analysis for ship structures. In the fourth and fifth papers, the non-Gaussian ship responses, computed by a 3D non-linear hydrodynamic code, are employed for investigating the accuracy of the proposed fatigue model and Laplace Moving Average (LMA) model for ship safety assessment. The last two papers establish a simple methodology for the computation of extreme ship responses. The scope of this thesis and connections between the papers are presented in Figure 3.1. Topics of the papers are summarized in Section 3.1. The more detailed summary of each paper is given in the following subsection.

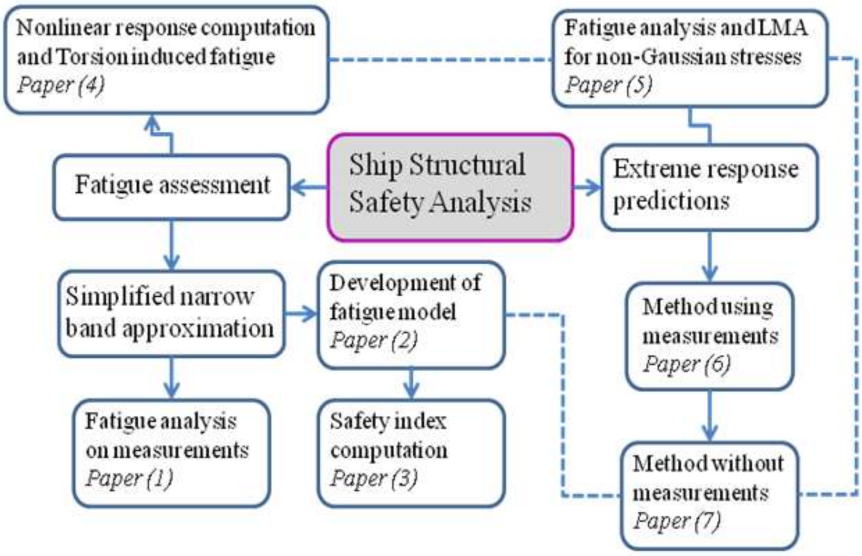

Figure 3.1, Scope of the thesis and connections between the appended papers

3.1 Categorized topics in each paper

3.1.1 Paper 1 ─ Comparison between a fatigue model for voyage planning and measurements of a container vessel

Presented at the OMAE 2009 conference.

Assessment of fatigue damage on ship structures, using the full-scale measurements of a 2800TEU container vessel, is carried out through:

- ✧ Check if one can split the measured long term stress history into a sequence of stationary sea states for fatigue estimates.
- ✧ A simplified narrow band approximation (NBA) for fatigue analysis is proposed. In the simplified NBA, significant stress range h_s is assumed to be proportional to the encountered significant wave height H_s with factor C, while zero upcrossing frequency f_z is approximated by encountered wave frequency.
- ✧ Verification of the two parameters h_s and f_z by the full-scale measurements.
- ✧ Comparison of fatigue damages estimated by the proposed model, rainflow counting method, and NBA carried out by the dedicated software.

3.1.2 Paper 2 ─ Development of a Fatigue Model Useful in Ship Routing Design

To appear in the SNAME Journal of Ship Research, Vol.54(4).

Investigate whether the proposed model in Paper 1 to estimate the damage accumulation is applicable when no measurement of stress history is available.

- ✧ Effect of whipping/springing on fatigue damage accumulation and the conservatism of NBA for the computation of fatigue damages are discussed.
- ✧ The factor C in $h_s \approx C \cdot H_s$ is estimated by a linear hydrodynamic theory. The value of C depends on the mission conditions. The frequency f_z is approximated by an explicit function of H_s derived by statistical analysis of long term distribution of sea conditions.
- ✧ Extensive validation of the developed fatigue model is performed using the full-scale measurements.

3.1.3 Paper 3 ─ Safety index of fatigue failure for ship structure details

Published in the SNAME Journal of Ship Research, Vol.54(3), pp. 197-208.

The proposed fatigue model in Paper 1 is applied to estimate the safety index of fatigue failure.

- ✧ The uncertainties due to the fatigue failure criteria, S-N curves and variable environments are first presented.
- ✧ The expression of safety index is derived for both parametric and non-parametric approaches.
- ✧ The non-parametric approach is then employed to estimate the safety index in

the future 5 years using the full-scale measurement during the first 6 months of 2008.

- ✧ The parametric approach employing the proposed fatigue model is also carried out to compute the safety index with H_s from a spatio-temporal variability model of significant wave height.

3.1.4 Paper 4 ─ Fatigue damage assessment of container ships concerning wave-induced torsion

Presented at the OMAE 2010 conference.

A more advanced commercial code, including nonlinear wave/structure interaction, is employed to compute the ship responses. The fatigue assessment is then performed based on the computed ship responses.

- ✧ The nonlinear behavior of the computed ship responses is first studied.
- ✧ The computed structural stresses are separated into different stress components, and compared with the full-scale measurements.
- ✧ The fatigue accumulation contributed by the vertical bending, horizontal bending and warping are investigated, respectively. The investigation is carried out for both head seas and oblique seas.
- ✧ The effect of different stress components on fatigue accumulation is studied in both deck and bottom of the ship.

3.1.5 Paper 5 ─ Estimation of Wave Loading Induced Fatigue Accumulation and Extreme Response of Container Ships in Severe Seas

Presented at the OMAE2010 conference.

This paper is the following-up work of paper 4. The computed ship responses are employed for the investigation in this paper.

- ✧ The proposed fatigue model in Paper 2 is used to estimate the damages caused by the numerically computed ship responses.
- ✧ The extreme ship responses, described by means of the upcrossing spectrum of non-Gaussian responses, are studied.
- ✧ It shows that LMA gives good predictions of extreme responses for both short term and long term estimates.

3.1.6 Paper 6 ─ Efficient estimation of extreme ship responses using upcrossing spectrum

Submitted to the MARSTRUCT 2011 conference.

The extreme ship responses (T-return values) are computed using the upcrossing spectrums at all encountered sea states. The corresponding upcrossing spectrums are computed from the full-scale measurements here. Results computed by the proposed method are validated and compared with some standard engineering methods.

- ✧ The probability of ship responses at high levels is shown to be well approximated by the corresponding upcrossing spectrums.
- ✧ The upcrossing spectrum of non-Gaussian ship responses is computed by the transformed Gaussian approach.
- ✧ The proposed method for estimation of extreme ship responses is validated by the standard engineering method. In the proposed method, all the parameters in the transformation for the computation of upcrossing spectrums are obtained from the measurements.

3.1.7 Paper 7 ─ Estimation of Extreme Ship Response

Under revision for the SNAME Journal of Ship Research.

Similarly as in Paper 2, this paper mainly focuses on investigation of whether the proposed method in Paper 6 is capable of estimating extreme ship response when no measurement is available.

- ✧ In Paper 6, it is shown that all the parameters in the transformation are somehow related with H_s. The standard deviation and zero upcrossing frequency of ship responses at each sea state are computed by the proposed method in Paper 2.
- ✧ Two examples are presented to explain the application of the proposed method for the computation of the extreme ship responses. The first example is carried out on the 2800TEU container vessel with skewness regressed from measurements. The second example is performed on a 4400 TEU container vessel, where all the parameters are computed from a nonlinear numerical analysis.
- ✧ For both examples, 3 different wave environment models are input into the method to estimate the extreme ship responses. It is found that having an accurate wave environment model is very important for the reliable estimation of the extreme ship responses.

3.2 Summary of each paper

3.2.1 Paper 1 ─ Comparison between a fatigue model for voyage planning and measurements of a container vessel

A fatigue model is proposed and studied in this paper to estimate fatigue damage accumulation along one voyage. The fatigue model is built up on the basis of the full-scale measurements of a 2800 TEU container vessel operating in the North Atlantic. The model is derived from the narrow-band approximation, see Eq. (6). It is shown that the predicted damage agrees well with the rainflow damage.

In this paper, a voyage is assumed to be composed of a series of stationary sea states, and each sea state lasts for 30 minutes. Two approaches (using the rainflow counting technique) to estimate the fatigue damage in one voyage are compared using the measured stress history. In the first approach, the fatigue damage at each sea state is computed separately, and then the total fatigue in a voyage is a sum of the damages induced at all sea states. In the second approach, the total fatigue damage is computed using the whole stress history during the voyage. (It is well known that the second approach always gives higher damages.) It is shown that the difference between the two approaches is small. Hence, the first approach is applicable for the fatigue analysis of ship structures.

The second part of the paper focuses on the estimation of the fatigue damage at each stationary sea state. The simplified NBA is proposed to estimate the damages. It includes two main parameters, i.e. significant stress range h_s and zero upcrossing response frequency f_z, see Eq.(8). The first parameter, h_s, is shown to be proportional to the significant wave height, H_s, with a factor C. The value of C is around 18.5 for head sea, and 13 for following sea, computed from the full-scale measurements. The second parameter, f_z, is approximated by the encountered wave frequency. It agrees well with the observed f_z for large sea states.

Finally, the proposed fatigue model (simplified NBA with factor C estimated from measurements) is compared with the standard NBA method where the parameters are computed by Eq. (8), and with the rainflow counting method. It is concluded that the proposed fatigue model works well for the head sea dominated voyages, while it should be improved for the following sea operations. The standard NBA approach, carried out by a commercial hydrodynamic code, greatly overestimates the fatigue damage of ship structures. The large difference is further investigated in the next paper.

3.2.2 Paper 2 ─ Development of a Fatigue Model Useful in Ship Routing Design

In this paper, the fatigue model proposed in Paper 1 is further investigated, while the parameters in the model are computed by a simple numerical analysis. Extensive validation of the proposed model is performed in comparison with the rainflow fatigue analysis.

According to the investigation on the full-scale measurements, ship response spectrums at all sea states are composed of both High-Frequency (HF) and Wave-Frequency (WF) responses. The HF ship responses contribute about 30% to the total fatigue damages. But only less than 3% of the response energy is induced by the HF responses. The conservatism due to the NBA can be used to balance the effect of non-Gaussian property of the measured ship responses.

Hence, in the NBA, h_s, proportional to the square root of the energy, can be computed using only the WF ship responses. The WF responses can be computed assuming a rigid body without any hydroelastic effects. Further, Gaussian responses are assumed so that the response spectrum (for calculating the energy) is computed by a simple linear numerical analysis in frequency domain. It is shown that the computed h_s agrees well with the observed results. Another parameter f_z is approximated by the encountered wave frequency, where the wave period is derived to be an explicit function of H_s from the conditional distribution of the wave period given H_s.

Since the standard numerical analysis (less time-consuming) considers only wave-induced response (WF), the effect of high frequency (HF) response on fatigue damage is studied. It is found that HF response contains only less than 3% of the total energy but contributes 30% of thetotal fatigue damage. It is checked that the Gaussian model for stresses gives very good predictions of observed rainflow damage.

The damage computed by the proposed model is greatly dependent on the distribution of H_s. The onboard measured H_s calibrated by satellites and H_s computed from a spatio-temporal wave model are applied into the model to compute the fatigue damage. The results agree well with the rainflow damages, with less than 20% discrepancy for both winter and summer voyages.

3.2.3 Paper 3 ─ Safety index of fatigue failure for ship structure details

The uncertainty in fatigue assessment is estimated by means of Cornell's safety index. The most difficult task for the estimation is the computation of the expectation and coefficient of variation of the accumulated fatigue damage. Two different approaches are presented. One is the non-parametric (statistical) approach using the measured stress history. The other is the parametric approach employing the fatigue model established in Paper 2.

The uncertainties caused by *S-N* curves and fatigue failure criterion are first reviewed in the paper. The safety index of ship structures is then described on the basis of three important assumptions, i.e. stationary shipping, no measurement errors, and independent shipping between different voyages.

The non-parametric approach is used to estimate the safety index of the same container ship with 6-month full-scale measurements for both middle section and after section. The fatigue damage in this approach is estimated using the rainflow cycle ranges. Assuming that the ship sails in the same routes and encounters the same wave environments in the future, the value of the safety index and the failure probability in 5 years is computed in the paper.

In order to apply the parametric approach, when no measurement is available, the fatigue model, proposed in Paper 2, could be employed for estimation of the fatigue damages. The model is described by an algebraic function of significant wave height, ship speed and heading angle. The parameter in the fatigue model is computed by a linear numerical analysis for both sections, and listed in the paper. The variability of significant wave height is modeled as a lognormal field with parameters estimated from the satellite measurements. The encountered significant wave heights H_s along shipping routes, are simulated from the wave model by a Monte Carlo method. Subsequently, the safety index is then computed using the simulated H_s.

The safety index, computed using the presented parametric approach, is compared with the index computed by the non-parametric approach discussed previously. It is shown that the two approaches give almost identical results. The analysis also indicates that fatigue cracks may be anticipated before the end of the ship's life. In the conclusion, it states that the proposed approach is applicable for safety assessment using very limited information. The deficiency of this approach is the possibility of "modeling errors", for example the linear transfer function could be too simple a model to describe the relationship between waves and stresses. Hence, the measurements may still be needed to validate the fatigue model for more general applications.

3.2.4 Paper 4 — Fatigue damage assessment of container ships concerning wave-induced torsion

This paper presents a standard approach for computation of the non-Gaussian ship responses. The effect of non-Gaussian properties and wave-induced torsion on fatigue damage is studied for a 4400 TEU container vessel. The ship responses are computed by a commercial hydrodynamic code, WASIM

Large deck openings of container vessels cause low torsion rigidity in oblique waves. The computation of fatigue damage for such vessels should consider different stress components at different locations. The wave loadings are computed by a commercial 3D code, using nonlinear hydrodynamic theory. The structural stresses are analyzed by the finite element method. The detailed procedures for the estimation of fatigue damages are also presented. In the middle section of the ship, the vertical bending moments are computed for sea states with significant wave height H_s equal to 3, 5, 7 and 10 m. It is shown that the computed response becomes more non-Gaussian as H_s increases.

In order to investigate the effect of torsion-induced fatigue, the techniques to separate different stress components, such as vertical bending induced stress, torsion-induced stress, etc., is also presented. It is found that the horizontal bending induced stress is coupled with the warping induced stress. For the oblique bow sea state conditions, the horizontal bending and warping induced stresses are in phase and superposed on the total stress in the deck areas. In the bottom areas, the two stress components are counteract.

Finally, the rainflow method is employed to compute the fatigue damage caused by the computed non-Gaussian stresses. The estimation is carried out for 5 different heading angles. Each heading angle is simulated with 2 speeds, i.e. service speed and half of the service speed. It is concluded that for the head seas, vertical bending contributes most of the fatigue damage, and the horizontal bending and warping can be disregarded in the middle section of the ship. But in oblique seas, the horizontal bending and warping contribute more to fatigue damage, and hence cannot be neglected for fatigue design. Further, it is shown that fatigue accumulation is greatly influenced by ship speed and heading angles.

3.2.5 Paper 5 ─ Estimation of Wave Loading Induced Fatigue Accumulation and Extreme Response of Container Ships in Severe Seas

The main tasks of this paper are: firstly, to check the accuracy of the simplified NBA method, proposed in Paper 2, for the estimation of damage, in the case of the computed non-Gaussian ship responses; secondly, to investigate the Laplace Moving Average (LMA) model for the computation of upcrossing spectrum of the computed ship responses. The target ship here is a 4400 TEU container vessel, which is presented in Paper 4.

After a brief review of methods on fatigue assessment and extreme prediction, this paper starts with a short introduction about the theory used in the 3D nonlinear hydrodynamic code. Ship responses at sea states with H_s = 3, 5, 7 and 10m, from head sea to following sea are computed by the numerical code. Then three different approaches, i.e. the rainflow counting method, the standard NBA of Eqs (7-8) (assuming Gaussian loads), and the simplified NBA proposed in Paper 2, are employed for computing the corresponding fatigue damage. It shows that the proposed simplified NBA gives almost identical results as the rainflow damages, while the standard NBA underestimates the damages for head seas. For the following seas, the proposed model underestimates the damages while the standard NBA gives good computations. However, most fatigue damages are accumulated in head seas.

The second part of the paper focuses on validation of the mathematical modeling of the non-Gaussian responses. The upcrossing spectrums of ship responses are then used to compute extreme ship responses. In the paper, the upcrossing spectrums are computed using Rice’s formula in Eq. (6), and the LMA model, respectively.

The upcrossing spectrums of ship responses, from both full-scale measurements of a 2800 TEU container vessel and a nonlinear numerical analysis (by WASIM) of another 4400 TEU container vessel, are used to compare Rice’s formula in Eq. (6) and LMA. It is shown that Rice’s formula as Eq. (6) greatly underestimates the upcrossing spectrum in the tail area, while LMA works well even for the ship responses at extreme high sea states. A crude extreme prediction is also performed after the upcrossing spectrum is obtained. This subject is further discussed in the next paper.

3.2.6 Paper 6 ─ Efficient estimation of extreme ship responses using upcrossing spectrum

This paper mainly investigates the efficiency of a method for the computation of extreme ship responses. In this method, the upcrossing spectrum should first be computed. The extreme response is then estimated from the upcrossing spectrum at high levels. The method is validated by the standard engineering approach using the full-scale measurements collected during a period of 6 months.

In the standard engineering approach, the long term cdf of ship response is fitted, for example, by a Weibull distribution. It shows that the probability of measured ship responses at high levels can be well described by a Weibull distribution. It fails in the case that ship responses are composed of a series of Gaussian processes. But the probability is shown to be well approximated by the upcrossing spectrum. Using the measurements, it is shown that two methods give the same extreme ship responses.

The transformed Gaussian approach proposed in *Winterstein (1988)*, combined with Rice's formula, is used to compute the upcrossing spectrum for the non-Gaussian ship responses. In the approach, the standard deviation, zero upcrossing frequency, skewness and kurtosis of ship responses, are needed. The first two parameters have been widely studied in Paper 2. In this paper skewness is regressed in terms of H_s from the measurements. It is found that the skewness is almost not influenced by the HF responses. Further, it is shown that the computation of the upcrossing spectrum is not sensitive to kurtosis. This method is verified using H_s from both onboard measurements and the DNV recommendation.

Finally, it is shown that the 100-year stress, computed using the upcrossing spectrum from the full-scale measurements, is consistent with that computed by the standard engineering method.

3.2.7 Paper 7 ─ Estimation of Extreme Ship Response

This paper presents an efficient methodology for extreme response prediction when no measurement is available. In this method, the long term responses are decoupled into several short term stationary responses (sea states). The extreme ship responses are computed using the upcrossing spectrum at all encountered sea states.

Ship response at each of the sea states is assumed to be non-Gaussian, and modeled by the transformed Gaussian approach, proposed by *Winterstein (1988)*. The corresponding upcrossing spectrum is then computed by Rice's formula. The upcrossing spectrums at all encountered sea states are then collected together for computing the extreme ship response.The capability of this method for extreme response prediction has been proven in Paper 6. The main task in the paper is to study the parameters needed for the computation of upcrossing spectrums. The distribution of sea states (H_s) and their effect on extreme responses are also widely discussed.

The same as in Paper 6, the first two parameters are expressed by those stated in Paper 2. The skewness is computed by a nonlinear numerical analysis assuming a rigid body, since the high-frequency responses do not affect the computation of skewness. It is shown that skewness is also proportional to H_s. The great importance of H_s for extreme response prediction motivates the investigation of different available ways of describing the distribution of H_s. In the paper, H_s from onboard measurements, the DNV recommendation, and an established spatio-temporal model are compared. It is presented that the extrapolation of observed H_s gives too low a probability of large sea states, with respect to the other two ways. The onboard routing plan system and limite time for measurements may be the reason for such a low probability. However, it also states that using the DNV recommended distribution of H_s leads to significant underestimation of fatigue damage with respect to the other ways.

Finally, the extreme ship responses, i.e. 20-year, 50-year and 100-year stresses, are computed for two different vessels. For the computation of a 2800 TEU container vessel with measurements, the standard deviation and zero upcrossing frequency are computed using the model in Paper 2. Skewness is regressed as a function of H_s. It is shown that the extreme responses, computed by the proposed method here, are close to those computed by the standard engineering approach. However, if the onboard measured H_s is used, the results significantly deviate from those computed using H_s from the other two approaches. For the other 4400 TEU container vessel, the application of this method is presented using all the three ways of H_s, while all the parameters in the computation are obtained from a nonlinear numerical analysis. However, the results greatly depend on the source of H_s.

Chapter 4
Conclusions

4.1 Contribution and major findings

Fatigue strength and ultimate strength of ship structures are of an essential issue for ship structural design. It is also important to monitor, by inspection and computation, the safety level of the ship structures after the ship has been launched. In this thesis, x a simple but reliable model is proposed for the computation of fatigue damage accumulation, and an efficient method for estimating the extreme ship responses is also established using the upcrossing spectrums. The fatigue model and the method for extreme response prediction are applicable for a ship routing program, and could even be used for ship conceptual design. The following main conclusions (findings) can be drawn from the work in the thesis:

On the fatigue assessment:

- The ship response spectrum at almost all sea states contain two peaks (bimodal spectrum). The low-frequency (WF) part is related to the wave-induced responses, and high-frequency (HF) part may be caused by the transient load or resonant vibrations, known as whipping/springing.
- Less than 3% of the response energy is caused by HF responses (whipping/springing). About 30% fatigue damage is contributed from HF whipping/springing
- For the computation of fatigue damage in ship structures, the damage can be analyzed separately for each sea state, and then added to give the damage in a voyage.
- Fatigue accumulation at sea states with H_s less than 2m, only causes 6% of the total fatigue damage.
- The real ship response in the middle section is slightly non-Gaussian. But the simulated Gaussian process, which has the same spectrum as the real ship response, causes the same fatigue damage as the real ship response.
- The narrow-band approximation overestimates the wave-induced (WF) responses at a level of 33% in average, which balances the HF contribution.

- ✧ The significant stress range h_s in the proposed fatigue model, is proportional to the encountered H_s with a factor C. The value of C is dependent on heading angles, ship speed for each individual sea state. From the long-term point of view, C is equal to 18.5 for the mid-section and 13 for the after-section of the investigated 2800 TEU container vessel.
- ✧ When no measurement is available, C can be computed by a linear numerical analysis for ship structures.
- ✧ Another parameter in the narrow-band approximation, i.e. zero upcrossing frequency f_z, is extremely influenced by the cut-frequency when computed by the spectral moments of ship responses. Hence, f_z is proposed to be approximated by the encountered wave frequency. It works well for the fatigue model.
- ✧ For long term fatigue estimations, the wave period T_z can be computed by an explicit function of H_s. The function can be obtained from the long-term conditional distribution of T_z given H_s, recommended by the DNV rule.
- ✧ The proposed fatigue model works well not only for the measured stress histories, but also for ship responses computed by linear and nonlinear numerical analysis.

On the extreme response prediction

- ✧ The long term cumulative distribution function (cdf) of the measured ship responses at high levels can be fitted by a Weibull distribution. However, if the ship responses are assumed to be composed of a series of stationary Gaussian processes, the Weibull distribution significantly overestimates the corresponding probability at high levels.
- ✧ The long term cdf at high levels can always be well approximated by the upcrossing spectrums.
- ✧ Extreme response prediction using the upcrossing spectrum is an efficient approach for the computations.
- ✧ The Laplace Moving Average model and the transformed Gaussian approach are accurate ways for modeling the real non-Gaussian ship responses.
- ✧ The parameters needed in the transformed Gaussian method are standard deviation, skewness, kurtosis and zero upcrossing frequency of the ship responses at each sea state. The standard deviation and zero upcrossing response frequency can be computed using the same expressions as proposed in the fatigue model.
- ✧ Skewness does not depend on the high frequency ship responses, i.e. whipping/springing. The skewness can be computed using a nonlinear numerical hydrodynamic code assuming a rigid ship body. Kurtosis is not so sensitive to the computation of upcrossing spectrums.
- ✧ The distribution of H_s (at high levels) is very important for the computation of the extreme ship responses. Using the onboard measured H_s leads to a large underestimation of extreme ship responses, in comparison with those using

DNV recommended H_s and H_s from the spatio-temporal wave model proposed in Baxevani et al. (2009). However, using the onboard measured H_s results in larger fatigue accumulation than the DNV recommended H_s.

4.2 Suggestions for future work

The long term objective of this thesis based project is to develop a robust code for ship routing design with respect to fatigue accumulation and extreme loading. Obviously, this is an important task in the future, and the two proposed models serve as the basis for the future work. However, firstly, these two models should be further investigated and validated for more general applications. Moreover, it is recommended that more studies are needed on the accurate stochastic models for the wave environments in different ocean regions.

4.2.1 On the fatigue model

The proposed fatigue model is developed and validated, using the full-scale measurements of a 2800 TEU container vessel. It also works well with ship responses computed by a nonlinear numerical analysis to another 4400 TEU container vessel.

However, the proposed model is mainly employed for estimating the fatigue damages in the middle section of container ships. Fatigue cracks are often found in other parts of ships, whose fatigue damage it should also be able to estimate by the proposed model. Further, fatigue estimates of container vessels are less complex than other types of ships, due to the fact that container vessels usually operate under one single loading condition, i.e. full load condition. The other type of ships, such as tankers and bulk carriers, always operates under both load and ballast conditions. The fatigue model should be improved for estimating the fatigue damage of ships under ballast conditions. Moreover, the ship structural details vary for different ship types. It is recommended that the proposed model should be further improved to consider all these variations.

It is also important to accurately compute local structural stress when estimating fatigue damage of ship structures. In this thesis, a crude stress concentration factor (SCF) with the value 2 is used for considering the local characters of ship details. But SCF should be accurately determined for practical applications. It is strongly suggested to further study the values of SCF by, for example, either a local FE-analysis, or alternatively, choosing from the classification society rules.

4.2.2 On the methodology of extreme predictions

The transformed Gaussian approach is used to model non-Gaussian ship responses in this thesis. Further study on the computation of extreme ship response can focus on the establishment of models for some parameters in the method, such as skewness and kurtosis, for different locations and ship types. The standard deviation of ship responses can be directly computed using the expression in the fatigue model. It is reported that non-Gaussian properties of ship responses under the ballast condition could be more important than that under the load condition. The high frequency responses (whipping/springing) might also significantly influence the values of skewness. All these characters are recommended for further study in the future research.

Further, with the standard engineering approach (using Weibull to fit the long term cdf), it is possible to estimate the extreme ship response using the measurements. Preliminary study of the full-scale measurements indicates that the fitted Weibull distribution is actually exponential with the rate parameter related to the mean standard deviation of all the encountered sea states. Obviously, more work is suggested in order to find the general rules for computing the two parameters for different ship types and ship locations. The possible results will significantly benefit ship design for the computation of the extreme ship responses.

4.2.3 On the distribution of wave environments (mainly H_s)

Estimation of fatigue damage accumulation requires accurate models for variability of the encountered wave environments, i.e. significant wave heights H_s during a ship's service period. The comparison of different proposed data sets for the long term cdf of significant wave height is needed.

A more complex spatio-temporal model that includes significant wave height and wind speed should be developed, for ship safety assessment and for the analysis of loads for offshore placed windmills. Here, one needs to study the conditional spatio-temporal field given meteorological predictions. For ship routing design, it would be good to work on a model for the size and dynamics of storms.

Chapter 5
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